Summary Information

I. Winter Measurements of Heavy-duty Vehicles to Characterize the Cold Temperature Effectiveness of Selective Catalytic Reductions Catalyst in Controlling Oxide of Nitrogen Emissions

II. University of Denver, Department of Chemistry and Biochemistry, Denver, CO. 80208, Gary A. Bishop (PI), 303-871-2584, gbishop@du.edu

III. Leighann Rawls, Office of Research and Sponsored Programs, University of Denver, Denver, CO. 80208, 303-871-4053, Leighann.rawls@du.edu

IV. Funding Requested: $52,000.00
Matching funds: $0

V. Project Period: 8/1/2020 – 7/31/2021

Scope of Work

Abstract

The Salt Lake City region in Utah experiences periods of high particulate levels in the winter months due to the combination of its topography, winter atmospheric inversions and local emissions. Secondary nitrite particles comprise the dominate fraction of the particles in these episodes and are the result of the reaction of oxides of nitrogen with ammonia. Recent research has shown that peak wintertime $PM_{2.5}$ concentration maxima have not been reduced along with the summertime maxima NO_x indicating a possible difference in the winter inventories. One possible explanation for these differences is that the NO_x emissions inventory is underestimated during the winter months. In addition work in Europe on light-duty diesel vehicles has shown a significant temperature dependence in NO_x emissions with emissions increasing with decreasing temperature.

A significant fraction of NO_x emissions in the Salt Lake City area are produced by heavy-duty vehicles operating in or traveling through the area on the interstate highway system. New technology in the form of selective catalytic reduction catalysis to control NO_x tailpipe emissions have been entering the heavy-duty fleet since 2011 and winter-time performance of these systems has received little attention. Because of the importance of winter-time NO_x emission factors from heavy-duty vehicles to the Salt Lake City NO_x inventory we are proposing to conduct a winter-time measurement campaign to measure them.

Using the University of Denver's (DU) remote vehicle exhaust sensor we propose to measure heavy-duty vehicle emission factors for carbon monoxide, hydrocarbon, nitric oxide, nitrogen dioxide and ammonia from in-use vehicles in the Salt Lake City area. A week of measurements at a weigh station or other location frequented by heavy-duty vehicles will produce 1000 or more measurements allowing a detailed look at the emissions distribution of the heavy-duty vehicle fleet during winter temperature conditions. This data will allow the direct emissions comparisons between similar model year vehicles to data collected in other areas of the country during warmer weather. This data set should also allow the current inventory for the Salt Lake City area to be compared to an updated version using these new wintertime emission values.

Basis and Rationale

In the Salt Lake City region fine particulates accumulate during periods of low winds and thermal inversions where warm air aloft traps the air mass against the ground and mountains to the west. As a consequence, the region has a serious designation for violation of the 24-hour $PM_{2.5}$ standard. In 2017, the Utah Winter Fine Particulate Study was conducted to investigate the sources, composition, and chemistry of the fine particulates (1). Figure 1 shows the composition of submicron particles ($PM_{1.0}$) as measured by the National Oceanic & Atmospheric Administration's (NOAA) Twin Otter, which was instrumented with an aerosol mass spectrometer. As illustrated, during cold-pool air pollution episodes, the dominant fraction of $PM_{1.0}$ is nitrate (blue pie ~ half of total). Nitrate (NO_3^-) reacts with ammonia (NH_4^+) to form ammonium nitrate aerosol. When taken together, ammonium nitrate (blue + orange pies) accounts for nearly ~80% of the $PM_{1.0}$ during episodes. Therefore, it is critical to understand sources that contribute to both NO_3^- and ammonia (NH_3).

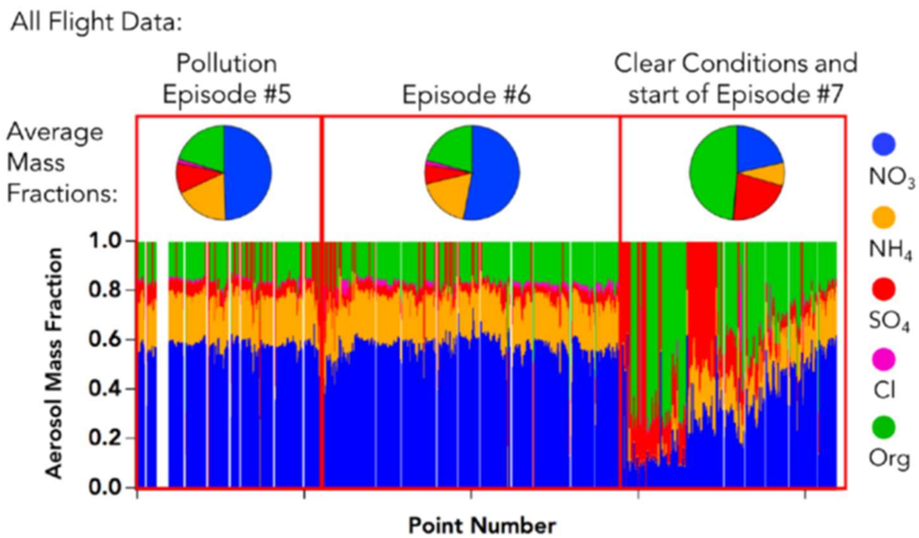

Figure 1. Composition of submicron particulate matter ($PM_{1.0}$) in Salt Lake City during the 2017 Utah Winter Fine Particulate Study (Baasandorj et al., 2018). During cold-pool episodes, nitrate is the dominant fraction of the $PM_{1.0}$ mass.

The main source of nitrate is expected to be oxides of nitrogen ($NO_x \equiv NO + NO_2$), of which emissions from transportation and stationary sources are known to be important precursor emissions in the formation of fine particulate matter ($PM_{2.5}$) (2-4). A steady reduction in mobile source NO_x emissions has occurred over the previous two decades due to the implementation of new emissions control technologies (5-7). However, the U.S. Environmental Protection Agency estimated that in 2018 on a national basis mobile sources (highway vehicles and non-road mobile) still account for almost 60% of the total NO_x emissions (8).

Heavy-duty vehicles account for the largest share of the NO_x emissions in the on-road fleet despite only representing a small fraction of the fleet. They have been the focus of recent regulations to dramatically lower tailpipe particle and NO_x emissions. These regulations have made significant improvements in emissions, though cold operating performance of the catalytic emissions control systems have raised questions regarding their overall performance (9-10). Selective catalytic reduction (SCR) systems have been universally installed to reduce engine out NO emissions to nitrogen but these systems require high operating temperatures (>200° C) to function. Below these temperatures the current regulations exempt the engine manufacturer from meeting the tailpipe certification standards.

The performance of diesel engines at colder temperatures has become important as recent research has shown that peak wintertime $PM_{2.5}$ concentration maxima have not been reduced along with the summertime maxima (11). In addition, recent research from Europe has shown a NO_x temperature dependence with increasing emissions at lower temperatures, even for vehicles with the newest after-treatment systems (12). Current computer models only include a temperature dependence for air conditioning operation at high temperatures and likely underestimate wintertime NO_x levels. Furthermore, preliminary modeling evidence over the Continental US from co-investigator McDonald, illustrates that current inventories of US NO_x emissions perform well for summertime (Figure 2, left: model bias = -3%) and under-predict significantly in the wintertime (Figure 2, right: model bias = -59%). The model was simulated with NO_x emissions updated to 2018 utilizing a Fuel-based Inventory of Vehicle Emissions (FIVE) developed by co-investigator McDonald for mobile sources, continuous emissions monitoring system data for power plants, and the National Emissions Inventory 2014 for all other sources (13). The model under-predictions are even more pronounced over the urban areas, such as New York City, suggesting a missing or under-accounted urban source. We hypothesize that a potentially significant under-accounted source of wintertime NO_x emissions are from heavy-duty diesel trucks instrumented with SCR systems.

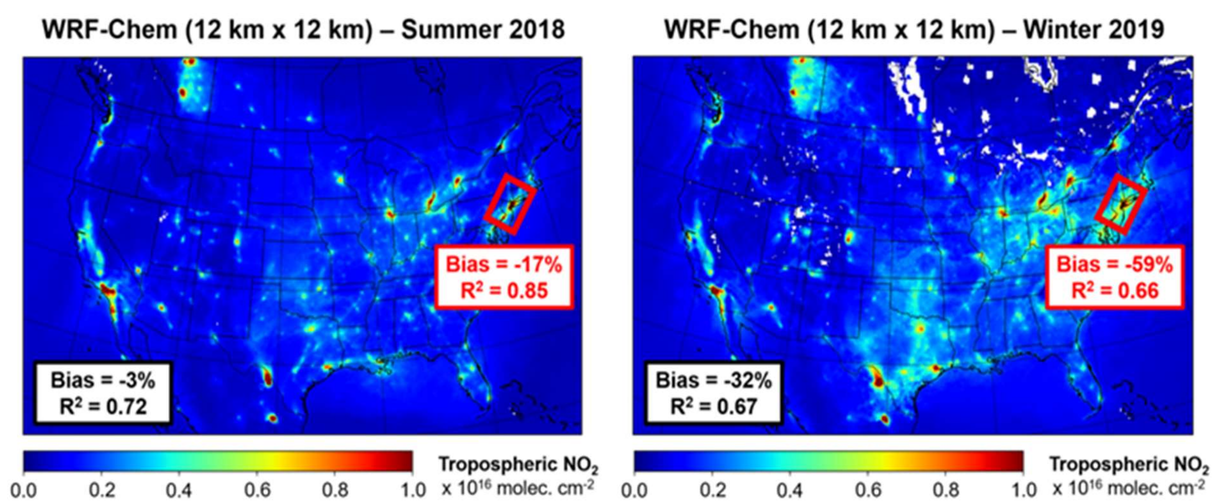

Figure 2. Modeling Continental US NO_x emissions in the Weather Research and Forecasting with Chemistry (WRF-Chem) Model and evaluations with tropospheric NO_2 satellite columns from the Tropospheric Ozone Monitoring Instrument for (left) summer and (right) winter.

While there are a significant number of emission measurements that investigate the performance of heavy-duty SCR systems, the majority of these measurements have been performed in

California at warm temperatures (7, 14-16). Little is currently known about the cold temperature performance of these catalytic systems in the current heavy-duty vehicle fleet and the temperature effects on their NO_x and NH_3 emissions. This lack of information potentially handicaps the current Salt Lake City inventories and efforts to address $PM_{2.5}$ reduction efforts. We therefore propose to conduct a winter sampling campaign in the Salt Lake City region of the Wasatch Front to measure the tailpipe emissions of heavy-duty vehicles operating in that region. This data will allow the direct emissions comparisons between similar model year vehicles to data collected in other areas of the country during warmer weather. This data set should also allow the current inventory for the Salt Lake City area to be compared to an updated version using these new wintertime emission values. For example, the emission factors collected could be used to update the inventory in Figure 2, to assess whether the wintertime under-prediction in the NO_2 columns are closed.

Technical Approach

Task 1 – Site Selection and Permission

In consultation with the Utah Division of Air Quality a suitable location to measure the exhaust emission of on-road heavy-duty vehicles will be selected. The site needs to have a single lane roadway with shoulder areas that are large enough to allow the installation of the measurement equipment and support vehicle. Ideally we would like the location to be in the general Salt Lake City area. However, heavy-duty vehicles travel large distances and their emissions are not location dependent and so other locations that meet the goals of the project can be considered. The chosen site will have to have winter daytime operations and a large enough volume of heavy-duty vehicles to allow the collection of emission measurements from at least 1000 vehicles during five days of work.

An example of one possible location that could likely satisfy all the requirements is the Utah Department of Transportation Perry Port of Entry located on I-15 between Perry and Ogden Utah. The site has a single lane exit and plenty of room to install the emission monitoring equipment and should have adequate heavy-duty vehicle traffic. We currently have no information on this stations operating hours but it likely has a schedule that would suit this project. After the locations are identified DU will contact the appropriate authorities to gain the necessary permission to make the emission measurements.

Task 2 – Emission Measurement Campaign

DU will travel to the site, install, and operate a remote sensing system that is capable of measuring the exhaust emissions of heavy-duty vehicles during actual operation. DU is uniquely qualified to collect these types of measurements and has conducted more than twenty of these types of measurement campaigns since the late 1990's. The goal for this project is to collect five days of low temperature exhaust measurements from in-use heavy-duty vehicles that are operating in and around the Salt Lake City area. This will be the first time that wintertime in-use emission measurements will have been collected in the US from in-use heavy-duty vehicles and the data will enable the evaluation of the effectiveness of new catalytic emission controls at these temperatures. This will require the measurements to be collected during the November to

January time frame. Using historical temperature data from the Ogden airport the period between Thanksgiving and Christmas is likely to provide the best temperatures for the measurements to be collected.

The FEAT remote sensor to be used in this study was developed at DU for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature (17-19). The instrument consists of a non-dispersive infrared (NDIR) component for detecting carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and percent opacity, and two dispersive ultraviolet (UV) spectrometers for measuring NO, NO_2, sulfur dioxide (SO_2), and NH_3. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement (see Figure 3). Collinear beams of IR and UV light are passed across the roadway into the IR detection unit, where the beams will be focused onto a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC, and reference (opacity is determined by plotting reference vs. CO_2). The UV light is reflected off the surface of the beam splitter and is focused onto the end of a quartz fiber-optic cable, which transmits the light to the two UV spectrometers. The UV spectrometers are capable of quantifying NO, NO_2, SO_2, and NH_3 by measuring absorbance bands in the regions of 205 - 226 nm, 429 - 446 nm, 200 – 220 nm, and 200 - 215 nm, respectively, in the UV spectrum and comparing them to calibration spectra in the same regions.

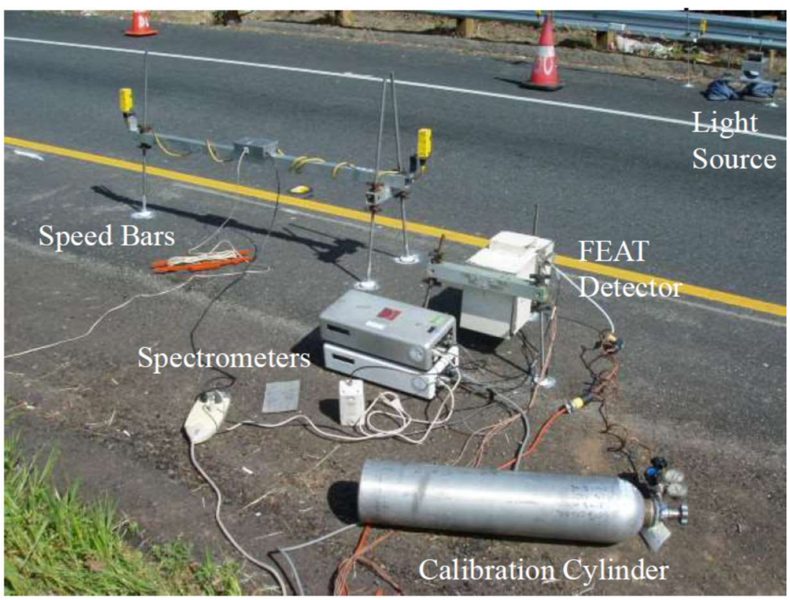

Figure 3. FEAT system setup at ground level showing the various components.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor only directly measures ratios of CO, HC, NO, NO_2, NH_3, SO_2 to CO_2. These measured ratios can be converted directly into grams of pollutant per kg of fuel. This conversion is achieved by first converting the pollutant ratio readings to the moles of pollutant per mole of carbon in the exhaust from the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q+1+6Q'}$$

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming the fuel is stoichiometrically CH_2. The HC/CO_2 ratio must use two times the reported HC because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon flame ionization detector reading (20). Grams per kg of fuel can be converted to g/bhp-hr by multiplying by a factor of 0.15 based on an average assumption of 470 g CO_2/bhp-hr (21).

The FEAT detectors will be calibrated as external conditions warrant from certified gas cylinders containing known amounts of the measured species ratioed to CO_2. This ensures accurate data by correcting for all external factors such as ambient temperature, instrument drift, background CO_2 levels etc. with each calibration. Due to the reactivity of NO_2 with NO and NH_3 with CO_2, three separate calibration cylinders are needed: 1) CO, CO_2, propane (HC), NO, N_2 balance; 2) NO_2, CO_2, air balance; 3) NH_3, propane, balance N_2. Since the removal of sulfur from U.S. fuels we no longer calibrate for or report SO_2 measurements.

The FEAT remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The images are stored digitally, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of the trucks driving past the remote sensor will also be used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, six feet apart and approximately four feet above the surface. Vehicle speed is calculated from the average of two times, collected when the front of the tractors cab blocks the first and the second beam and the rear of the cab unblocks each beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s.

The current US heavy-duty fleet is a mix of trucks with elevated and ground level (~30%) exhaust pipes. The latter only recently since trucks with 2010 compliant engines joined the fleet. For elevated exhaust pipes it is necessary for the detection beam to be elevated above the top of the truck. The light source and detector will be positioned atop a pair of aluminum scaffolding at an elevation of 13’3”, making the sensing beams and detector at an elevation of approximately 14’3”. Ground level measurements will be performed by simply placing the detectors and light sources on the roadway and measuring the exhaust emissions from underneath the truck (see Figure 4). Behind the scaffolding will be DU’s mobile lab housing the auxiliary instrumentation (computers, calibration gas cylinders and generator). Speed bar detectors will either be attached

Figure 4. Photograph of a dual FEAT setup at the Peralta Weigh Station to detect both elevated exhaust emissions (atop the scaffolding) and ground level exhaust from heavy-duty diesel trucks.

to each scaffolding unit or ground mounted to report truck speed and acceleration. A video camera will be placed down the road in front of the truck taking pictures of license plates when triggered by the vehicle. We currently only have a single FEAT unit for this work and anticipate sampling 3 days from elevated exhaust pipes and 2 days from ground level exhaust trucks to fully cover both fleets.

In addition to exhaust gas detection the FEAT system will also include a FLIR A20 thermal imaging sensor that will be used to capture thermographs of the passing trucks exhaust pipes. Since NO_x emission control in modern diesel vehicles now involves a catalyst that's operation is temperature dependent. We will utilize the exhaust pipe thermographs in an attempt to gauge catalyst operating temperature. This method is imperfect as some vehicles have shielded exhaust pipes that cannot be imaged and external pipes that are visible are downstream of the catalyst and are likely cooler than the actual catalyst temperature. However, we have found that the thermographs can provide a site temperature distribution that can be utilized to estimate the fraction of trucks that are at normal operating temperatures. Figure 5 shows a sample thermograph captured in a previous measurement campaign at the Peralta weigh station in southern California. The thermograph images will be visually reviewed and scored using a calibration curve determined from actual thermocouple field measurements of more than 200 trucks (22). These operating temperatures, when available, will be part of the final emissions database.

Because we are interested in the impact of ambient temperature on the emissions of the heavy-duty trucks we will also collect hourly ambient temperature data. Generally we prefer to use data collected at an official U.S. weather site provided they are in reasonably close proximity to the

Figure 5. Thermographic image of the exhaust pipe of a truck leaving the Peralta weigh station in California. The relative scale is from ambient temperatures (purple) to approximately 150° C (bright red).

emissions monitoring sites. If an official station is not deemed to be representative of the test area, then we will field our own weather collection system at the site and collect hourly averaged data to be included in the measurement database.

Task 3 – Database Creation and Analysis

Upon completion of the wintertime sampling campaign DU will assemble all of the valid emission measurements and transcribe the license plates for each valid measurement along with identifying the state of registration. The license plates will be matched to available vehicle registration records including out state plates. DU has relationships with several state authorities including California, Oregon, Colorado and Illinois and will submit these plates to their respective states. For other states DU may ask UDAQ for help in contacting Utah DMV to match Utah plates and will likely include a paid submission to IHS Markit (formerly R.L. Polk Automotive) for the remaining out of state plates.

Vehicle registration information will be combined with the emissions database and the combined database will be quality checked for obvious registration mismatches, which will be removed. After the databased has been finalized it will provide the basis for all of the statistical analysis for the final report. With model year information we will be able to segregate the emission measurements by model year and heavy-duty vehicle technology type.

In general vehicles with chassis model years of 2011 and newer can include engines that meet the U.S EPA and California 2010 heavy-duty engine emissions standards of 0.2 g/bhp-hr. However, because the industry was allowed to bank and trade emission credits to exempt certain engine families from meeting these standards and due to a lawsuit filed by Navistar not all heavy-duty vehicles built after 2010 meet that standard. However, the effect of temperature on NO_x and NH_3 emissions from these newer heavy-duty vehicles is the major emphasis of this research.

The data analysis will include fleet emission averages in molar emission ratios and in grams/kilogram of fuel consumed for all the species measured along with standard error of the mean uncertainty estimates for the heavy-duty vehicles with elevated exhaust and those with ground level exhaust. Fleet mean emissions as a function of ambient temperature will be explored in depth. In addition the relationship between emissions and vehicle model year for both exhaust types will be analyzed. Thermal imaging information will be used to gauge what if any influence it may have on the NO_x and NH_3 emissions from the 2011 and newer vehicles. The NO_x and NH_3 collected at the proposed Utah site will be compared to those collected at other sites in other states during warmer months, and model predicted values will be used to determine what if any differences exist and how those differences manifest themselves.

The mean emission values for all of the measured species can be combined into a fleet average using an estimate of the fraction of each exhaust type. This fleet mean can then be used to calculate the heavy-duty emissions inventory for the Salt Lake City area and compare that to other model estimates. Any differences will be investigated and commented on. There will likely be additional topics that will come up as the data is analyzed and these will also be included in the final report.

Task 4 – Dissemination of Results (Deliverables)

Three quarterly reports will be submitted using the provided template to UDAQ for each quarter after the onset of the project. Upon completion of the data analysis a draft final report will be prepared detailing the emissions measurement project and will include all the elements required in the request for proposals. An example of a final report prepared for a project of this type can be found here (http://www.feat.biochem.du.edu/assets/databases/Cal/CA_HDDV_final_report_2012_NREL_version.pdf). The draft will be submitted to UDAQ for comments no later than 90 days after the completion of the project. Any comments will be included into a final report which will be delivered to UDAQ along with the emissions database. Upon acceptance of the final report by UDAQ the report and the database will be posted to the FEAT website (www.feat.biochem.du.edu) where they will permanently reside and be publicly available.

The results will be communicated at the Science for Solutions conference and will likely be communicated at the Coordinating Research Council's annual Real World Emission Workshop. In addition the results will be distilled and submitted for publication in an international scientific journal.

Schedule

The current proposed work schedule would have a starting date of August 1, 2020. This would allow sufficient time to select a measurement site and secure the necessary permissions to collect the measurements, allowing the measurements to be collected in the November to January time frame as weather conditions allow. License plate transcription will follow the completion of the sampling campaign and after matching those plates to registration records the analysis of the measurements will begin. After completion of the analysis the data will be used to prepare the final report.

Table 1. Proposed Monthly Work Plan

Months	1	2	3	4	5	6	7	8	9	10	11	12
Tasks												
1. Siting and Permission	**	**	**	*								
2. Sampling Campaign				*	**	**						
3. Database and Analysis							**	**	**	**		
4. Dissemination of Results											**	**
Quarterly Reports				*			*			*		

Personnel Roles and Responsibilities

Gary Bishop (DU) will be the PI for this project and will oversee and perform aspects of all the tasks previously listed. Gary will conduct the siting search and secure all the necessary permissions to conduct the measurements. Gary will provide the DU remote sensing equipment, research vehicle and all of the necessary supplies needed to conduct and collect the measurements. Gary will travel to the Salt Lake City area to collect the emission measurements and then transcribe and match the vehicle license plates. Gary will create the emission measurement database and be involved in all of the data analysis of those measurements. Gary will also be responsible for preparing the final report and any other scientific presentations. Gary's vita is attached below.

Brian McDonald (NOAA, volunteer collaborator) will be an in-kind contributor for this project and will travel with Gary to the Salt Lake City area and provide needed assistance during the sampling campaign. Brian will provide an important second opinion as the data analysis proceeds and inventory comparisons are prepared. Brian's vita is attached below.

References

1. Baasandorj et. al., 2017 Utah Winter Fine Particulate Study, Final Report submitted to the Utah Division of Air Quality, March, 2018.

2. Haagen-Smit, A. J.; Fox, M. M., Photochemical ozone formation with hydrocarbons and automobile exhaust. *J. Air Pollut. Control Assoc.* **1954,** 4, 105-109.

3. Pollack, I. B.; Ryerson, T. B.; Trainer, M.; Parrish, D. D.; Andrews, A. E.; Atlas, E. L.; Blake, D. R.; Brown, S. S.; Commane, R.; Daube, B. C.; de Gouw, J. A.; Dubé, W. P.; Flynn, J.; Frost, G. J.; Gilman, J. B.; Grossberg, N.; Holloway, J. S.; Kofler, J.; Kort, E. A.; Kuster, W. C.; Lang, P. M.; Lefer, B.; Lueb, R. A.; Neuman, J. A.; Nowak, J. B.; Novelli, P. C.; Peischl, J.; Perring, A. E.; Roberts, J. M.; Santoni, G.; Schwarz, J. P.; Spackman, J. R.; Wagner, N. L.; Warneke, C.; Washenfelder, R. A.; Wofsy, S. C.; Xiang,

B., Airborne and ground-based observations of a weekend effect in ozone, precursors, and oxidation products in the California South Coast Air Basin. *Journal of Geophysical Research* **2012,** 117 (D00V05), 1-14.

4. Zhang, R.; Wang, G.; Guo, S.; Zamora, M. L.; Ying, Q.; Lin, Y.; Wang, W.; Hu, M.; Wang, Y., Formation of Urban Fine Particulate Matter. *Chem. Rev.* **2015,** 115 (10), 3803-3855.

5. McDonald, B. C.; Dallmann, T. R.; Martin, E. W.; Harley, R. A., Long-term trends in nitrogen oxide emissions from motor vehicles at national, state, and air basin scales. *J. Geophys. Res. Atmos.* **2012,** 117 (D18), 1-11.

6. Hassler, B.; McDonald, B. C.; Frost, G. J.; Borbon, A.; Carslaw, D. C.; Civerolo, K.; Granier, C.; Monks, P. S.; Monks, S.; Parrish, D. D.; Pollack, I. B.; Rosenlof, K. H.; Ryerson, T. B.; von Schneidemesser, E.; Trainer, M. C. G. L., Analysis of long-term observations of NO_x and CO in megacities and application to constraining emissions inventories. *Geophys. Res. Lett.* **2016,** 43 (18), 9920-9930.

7. Haugen, M. J.; Bishop, G. A.; Thiruvengadam, A.; Carder, D. K., Evaluation of Heavy- and Medium-Duty On-Road Vehicle Emissions in California's South Coast Air Basin. *Environ. Sci. Technol.* **2018,** 52 (22), 13298-13305.

8. Our Nation's Air: Status and trends through 2018. U. S. Environmental Protection Agency. https://gispub.epa.gov/air/trendsreport/2019/#air_pollution.

9. Misra, C.; Collins, J. F.; Herner, J. D.; Sax, T.; Krishnamurthy, M.; Sobieralski, W.; Burntizki, M.; Chernich, D., In-Use NOx Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines Equipped with Aftertreatment Devices. *Environ. Sci. Technol.* **2013,** 47 (14), 7892-7898.

10. Quiros, D. C.; Thiruvengadam, A.; Pradhan, S.; Besch, M.; Thiruvengadam, P.; Demirgok, B.; Carder, D.; Oshinuga, A.; Huai, T.; Hu, S., Real-World Emissions from Modern Heavy-Duty Diesel, Natural Gas, and Hybrid Diesel Trucks Operating Along Major California Freight Corridors. *Emission Control Science and Technology* **2016,** 2 (3), 156-172.

11. Chan, E. A. W.; Gantt, B.; McDow, S., The reduction of summer sulfate and switch from summertime to wintertime PM2.5 concentration maxima in the United States. *Atmos. Environ.* **2018,** 175, 25-32.

12. Grange, S. K.; Farren, N. J.; Vaughan, A. R.; Rose, R. A.; Carslaw, D. C., Strong Temperature Dependence for Light-Duty Diesel Vehicle NOx Emissions. *Environ. Sci. Technol.* **2019,** 53 (11), 6587-6596.

13. McDonald, B. C.; McKeen, S. A.; Cui, Y. Y.; Ahmadov, R.; Kim, S.-W.; Frost, G. J.; Pollack, I. B.; Peischl, J.; Ryerson, T. B.; Holloway, J. S.; Graus, M.; Warneke, C.; Gilman, J. B.; de Gouw, J. A.; Kaiser, J.; Keutsch, F. N.; Hanisco, T. F.; Wolfe, G. M.;

Trainer, M., Modeling Ozone in the Eastern U.S. using a Fuel-Based Mobile Source Emissions Inventory. *Environ. Sci. Technol.* **2018**, 52 (13), 7360-7370.

14. Preble, C. V.; Harley, R. A.; Kirchstetter, T. W., Control Technology-Driven Changes to In-Use Heavy-Duty Diesel Truck Emissions of Nitrogenous Species and Related Environmental Impacts. *Environ. Sci. Technol.* **2019,** 53 (24), 14568-14576.
15. Haugen, M. J.; Bishop, G. A., Long-Term Fuel-Specific NOx and Particle Emission Trends for In-Use Heavy-Duty Vehicles in California. *Environ. Sci. Technol.* **2018,** 52 (10), 6070-6076.
16. Dallmann, T. R.; DeMartini, S. J.; Kirchstetter, T. W.; Herndon, S. C.; Onasch, T. B.; Wood, E. C.; Harley, R. A., On-Road Measurement of Gas and Particle Phase Pollutant Emission Factors for Individual Heavy-Duty Diesel Trucks. *Environ. Sci. Technol.* **2012,** 46, 8511-8518.
17. Bishop, G.A.; Stedman, D.H. Acc. Chem. Res. 1996, 29, 489.
18. Popp, P.J.; Bishop, G.A.; Stedman, D.H. J. Air & Waste Manage. Assoc. 1999, 49, 1463.
19. Burgard, D.A.; Dalton, T.R.; Bishop, G.A.; Starkey, J.R.; Stedman, D.H. Rev. Sci. Instrum. 2006, 77, 014101.
20. Singer, B.C.; Harley, R.A.; Littlejohn, D.; Ho, J.; Vo, T. Environ. Sci. Technol. 1998, 32, 3241.
21. Broering, L. C. Diesel Engine Emissions Reduction History and Future Prospects, Cummins Engine Company, Presentation at the National Conference of State Legislatures, 1997.
22. Haugen, M. J.; Bishop, G. A., Repeat Fuel Specific Emission Measurements on Two California Heavy-Duty Truck Fleets. *Environ. Sci. Technol.* **2017,** *51* (7), 4100-4107.

Table 2. Proposed Project Budget

	Task 1	Task 2	Task 3	Task 4	Grand Total
Salary					
Bishop / DU months	$4078 0.5	$8156 1	$8156 1	$8156 1	$28546 3.5
Leave Reserve @ 17%	$693	$1387	$1387	$1387	$4854
Fringe Benefits @ 25.3%	$1207	$2414	$2414	$2414	$8449
Travel					
Lodging & Meals @ $151/day		$2416 16 days*		$453 3 days	$2869 19 days
Airfare				$250	$250
Rental Car		$300		$150	$450
Fuel		$610		$40	$650
Materials/Supplies					
Supplies		$205			$205
License Plate Match		$1000			$1000
Indirect Costs					
Indirect costs @10%	$598	$1649	$1196	$1284	$4727
Total Project Cost	$6576	$18136	$13153	$14135	$52000
Funds Requested					**$52000**

* 2 people for 8 days of sampling campaign for a total of 16 days of lodging and meals using the Federal per diem rate for Utah that includes lodging ($96/day) and meals ($55/day).

Budget Justification

Bishop monthly rate including leave reserve and fringe benefits - $11957/month

The University of Denver will cover the travel costs for McDonald for the data sampling campaign. The travel includes the time needed to drive to and from the Denver area, setup and an extra day for any weather delays during sampling and a rental car for the week of the measurements. Current Federal per diem rates for Utah were used to estimate the lodging and meal costs.

Travel for the Science and Solutions conference is included under task 4 for one person for 3 days (2 days for travel and 1 day for the conference). Per Diem for lodging and meals, roundtrip airfare from Denver to Salt Lake City and a rental car to reach the conference site are included.

License plate match is for out of state truck plates that need registration information.

Indirect costs have been applied to all costs at the UDAQ limited 10% rate.

GARY A. BISHOP (PI)
gbishop@du.edu

Office Address:
Department of Chemistry
University of Denver
Denver, CO 80208
(303) 871-2584

Home Address:
297 Lafayette St.
Louisville, CO 80027
(303) 665-4307

Education

B.S. in Chemistry, Berry College, Mt. Berry, Georgia, 1978.
M.S. in Bio-Physical Chemistry, University of Colorado, Boulder, Colorado, 1986.
Ph.D. in Bio-Physical Chemistry, University of Colorado, Boulder, Colorado, 1986.

Employment

University of Denver, Research Scientist since 1987.

More than 50 Peer Reviewed Publications. Some recent publications include:

Bishop, G. A., Three Decades of On-road Mobile Source Emissions Reductions in South Los Angeles. J. Air Waste Manage. Assoc. 2019, 967-976.

Haugen, M. J.; Bishop, G. A.; Thiruvengadam, A.; Carder, D. K., Evaluation of Heavy- and Medium-Duty On-Road Vehicle Emissions in California's South Coast Air Basin. Environ. Sci. Technol. 2018, 52, (22), 13298-13305.

Haugen, M. J.; Bishop, G. A., Long-Term Fuel-Specific NOx and Particle Emission Trends for In-Use Heavy-Duty Vehicles in California. Environ. Sci. Technol. 2018, 52, (10), 6070-6076.

Bishop, G. A.; Haugen, M. J., The story of ever diminishing vehicle tailpipe emissions as observed in the Chicago, Illinois area. Environ. Sci. Technol. 2018, 52, (13), 7587-7593.

Haugen, M. J.; Bishop, G. A. Repeat fuel specific emission measurements on two California heavy-duty truck fleets. Environ. Sci. Technol. 2017, 51, (7), 4100-4107.

Bishop, G. A.; Stedman, D. H.; Burgard, D. A.; Atkinson, O. High-mileage light-duty fleet vehicle emissions: Their potentially overlooked importance. Environ. Sci. Technol. 2016, 50, (10), 5405-5411.

Bishop, G. A.; Stedman, D. H. Reactive nitrogen species emission trends in three light-/medium-duty United States fleets. Environ. Sci. Technol. 2015, 49, (18), 11234-11240.

Brian C. McDonald (volunteer collaborator)
Research Scientist, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado and Chemical Sciences Division (CSD), NOAA Earth System Research Laboratory, 325 Broadway R/CSD4, Boulder, CO 80305
Phone: +1 (303) 497-5094, Email: brian.mcdonald@noaa.gov

Professional Preparation

Ph.D. Civil & Environmental Engineering, University of California, Berkeley, 2014
M.P.P. Goldman School of Public Policy, University of California, Berkeley, 2011
M.S. Civil & Environmental Engineering, University of California, Berkeley, 2011
B.S. Civil & Environmental Engineering, Virginia Tech, 2008
B.A. Economics, Virginia Tech, 2008

Appointments

2018 – present, CIRES/NOAA ESRL CSD, Research Scientist II
2016 – 2018, CIRES/NOAA ESRL CSD, Research Scientist I
2014 – 2016, CIRES/NOAA ESRL CSD, CIRES Visiting Postdoctoral Fellow

Selected Publications (5 out of 22 total, H-index = 12, advisees in ***bold italics***)

• **McDonald, B.C.**, et al. (2018). Volatile Chemical Products Emerging as Largest Petrochemical Source of Urban Organic Emissions. *Science*, 359, doi: 10.1126/science.aaq0524.

• **McDonald, B.C.**, et al. (2018). Modeling Ozone in the Eastern U.S. using a Fuel-Based Mobile Source Emissions Inventory. *Environmental Science & Technology*, 52, doi: 10.1021/acs.est.8b00778.

• ***Gorchov Negron, A.M.***, **B.C. McDonald**, et al. (2018). Development of a Fuel-Based Oil and Gas Inventory of Nitrogen Oxides Emissions. *Environmental Science & Technology*, 52, doi: 10.1021/acs.est.8b02245.

• Coggon, M.M., **B.C. McDonald**, et al. (2018). Diurnal Variability and Emission Pattern of Decamethylcyclopentasiloxane (D5) from the Application of Personal Care products in Two North American Cities. *Environmental Science & Technology*, 52, doi: 10.1021/acs.est.8b00506.

• Jiang, Z., **B.C. McDonald**, et al. (2018). Unexpected Slowdown of US Pollutant Emission Reduction in the Past Decade. *Proceedings of the National Academy of Sciences*, 115, doi: 10.1073/pnas.1801191115.

Synergistic Activities

• Presidential Early Career Award for Scientists and Engineers, *US Dept. of Commerce*, 2019
• Honorable Mention Colorado CO-LABS Governor's Award, 2018
• *Science* paper on consumer products selected for press briefing, *AAAS Annual Meeting*, 2018
• Co-organizer of NSF-sponsored workshop on "Evolutions in Urban Chemistry: Growing Influence of Non-Traditional Emission Sources" hosted at Univ. of Colorado, January 2019
• Member of Global Emissions Initiative (GEIA) working group improving global emission inventories of volatile organic compounds, an activity sponsored under the International Global Atmospheric Chemistry (IGAC) Project (2017 – present).